

PATENT APPLICATION

Docket No.: D497

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Title: Ceramic Ball Bearing Fracture Test Method

SPECIFICATION

Field of the Invention

The invention relates to the field of materials fracture testing. More particularly, the present invention relates to ceramic and metallic ball bearing fracture testing for manufacturing and qualifying high quality brittle ball bearings.

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Background of the Invention

Over the last decade, silicon-nitride Si_3N_4 balls have become an important component of advanced bearings used in a wide range of applications. The greatest commercial success for Si_3N_4 balls has been their use in hybrid bearings that combine the ceramic balls with steel races and that are known as silicon-nitride hybrid bearings. Compared to the steel balls, which the silicon-nitride balls replace, the ceramic balls are harder and less dense and offer higher compressive strength, better corrosion resistance, elevated operating temperature, and reduced lubrication requirements. These benefits make the hybrid bearings ideal for severe high-speed applications such as machine tool spindles, high speed dental drills, vacuum turbomolecular pumps, and the liquid-oxygen turbomolecular pumps used in the space shuttle main engines. Large diameter ceramic balls recently became the leading technology for hip replacements. The FDA requires fracture toughness testing of a substituted rectilinear specimen. Hence, a rigorous fracture toughness test that can be used by the FDA and orthopedic manufacturers is desirable for hip ball joints as well.

For exemplar future use in the space industry, the hybrid bearings have been proposed for the improved momentum control wheels and flywheels for satellites. Importantly, the hybrid bearings have recently been used in roller blades, an application where the bearings represent a mass marketing opportunity for lightweight rugged bearings. The roller blade

1 market, as well as other commercial applications, provides
2 recreational users and athletes with cost-effective high
3 technology long-lasting bearings with improved performance in
4 high volumes that would lower the price of the hybrid bearings
5 for all applications with increasing overall sales. For machine
6 tool spindles, the market for hybrid bearings was at \$35
7 million in 2000 and is projected to reach \$150 million by 2005,
8 and hence there is wide spread usage. The overall sales of
9 hybrid bearing should reach several hundred million by 2010.
10 Hence, there is a significant need for high-volume hybrid
11 bearings subject to repeatable and accurate manufacturing
12 requirements.

13
14 Ceramic balls have significant drawbacks and limitations.
15 Like all ceramics, the silicon-nitride balls have a low tensile
16 strength, which is a fundamental material property. Therefore,
17 under applied tension, the balls are prone to crack either at a
18 preexisting manufacturing flaw or at a flaw that develops
19 during service and usage. A closely related fundamental
20 material property is the fracture toughness, which indicates
21 the susceptibility to fracture of the ceramic material. Low
22 fracture toughness is most important factor indicating the
23 ruggedness and usefulness of all ceramics in general as well as
24 the silicon-nitride balls, in particular. Fortunately, highly
25 engineered ceramics have been developed whose fracture
26 toughness can be significantly increased through processing
27 that controls microstructures. Precise manufacturing can
28 control the size and number of preexisting flaws. To produce

1 tougher ceramics is therefore a two-fold task. First, a
2 microstructure is selected that is intrinsically tougher, which
3 reduces the severity of any flaws. Second, the preexisting
4 flaws are eliminated, which ameliorates the low fracture
5 toughness.

6
7 In the specific case of silicon-nitride balls,
8 manufacturing processing has been developed that provides, for
9 example, a two-phase microstructure of alpha and beta silicon
10 nitride where the minor second phase is a blocky shape in a
11 matrix of the major phase. As a micromechanism, this
12 microstructure promotes crack deflection and blunting, which
13 raises the intrinsic fracture toughness. In addition, the
14 ceramic balls are manufactured from a starting powder through
15 hot-isostatic pressing that is followed by grinding and lapping
16 to provide precise spherical shapes. Accurate control of the
17 hot-isostatic pressing eliminates sintering voids and
18 inclusions that are potential preexisting flaws leading to
19 potential fracture and failure of the balls. Precise control of
20 the grinding and lapping eliminates surface cracks. Inspection
21 and nondestructive evaluations are also used to screen balls
22 with preexisting flaws from usage especially in critical
23 applications.

24
25 Hence, it is highly desirable to have a manufacturing test
26 that measures the fracture toughness of mass produced silicon-
27 nitride balls. Ideally, the test should be simple and robust
28 enough to be used for quality control by manufacturers and for

1 qualification by contractors installing the balls in critical
2 applications. As an added benefit, a robust quality control
3 manufacturing screening test offers the ability to specify
4 fracture toughness, which is a basic material property, as a
5 purchasing requirement. The manufacturing screening fracture
6 toughness test can also be incorporated into statistical
7 process control on a manufacturing factory floor to reduce
8 cost, improve quality, and to evaluate independently the
9 success of the inspection and nondestructive evaluations. In
10 addition, the manufacturing screening fracture toughness test
11 can be used to research how changes in materials processing
12 control fracture toughness so as to provide testing feedback
13 between various manufacturing processes and mechanical behavior
14 of the ceramics.

15
16 There are basically two different classes of tests for
17 fracture toughness of brittle materials such as ceramics. The
18 first class is a direct measurement in which the applied stress
19 state at which a crack grows is measured. The second class is
20 based upon indentation techniques and is indirect because the
21 applied stress state is inferred from semiquantitative
22 estimates of residual stress based upon an indirect dimensional
23 argument. In the direct measurement, a starting crack or flaw
24 of known size and shape is placed in the test specimen. The
25 geometry of the starting crack directly gives the stress
26 concentration of the crack based upon either an analytical
27 solution or a finite element solution. The specimen is then
28 loaded so that the crack is under tension. Both the observed

1 applied load at which the crack grows and the calculated stress
2 concentration of the crack are combined to give directly the
3 ceramic fracture toughness of the ceramic. For a standard
4 direct test of fracture toughness, the fracture toughness is
5 defined by the observed load at which the crack grows and the
6 geometry of the starter crack, which provides the stress
7 concentration at the starter crack.

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9 Examples of direct measurements include the chevron notch,
10 bridge indentation, double cantilever beam and Tattersall-
11 Tappin tests. Unfortunately, these tests all use a rectilinear
12 or cylindrical specimen that typically has a largest linear
13 dimension that is on the order of several centimeters. In
14 contrast, ceramic balls used in even the largest capacity
15 hybrid bearings have a diameter of much less than 1.5 cm, which
16 makes it virtually impossible to fabricate specimens for any of
17 these standard fracture tests due to the spherical shape of the
18 balls and the limited volume of the balls.

19
20 As an alternative, the indentation test is currently used
21 in industry to measure the fracture toughness of the ceramic
22 balls. In this test, either a Vickers or Knoop indenter is
23 used to make a pyramidal indentation in the surface of the
24 ceramic. Indentation tests are indirect and semiquantitative.
25 At a sufficiently high applied indentation load, cracks can
26 grow from the corners of the indentation as the indentation is
27 loaded. The length of the produced cracks and the maximum
28 applied load are used to calculate the fracture toughness of

1 the ceramic. In contrast to the direct tests, crack growth is
2 not caused directly by the applied load but is instead caused
3 physically by accommodation of displaced material after the
4 crack is unloaded. The indentation test is, however, not
5 rigorously quantitative. The calculation is based upon an
6 estimate of the residual tensile stresses caused by the
7 indentation. The estimate is not based upon direct measurements
8 but is instead based upon a simple and crude dimensional
9 analysis. The calculation also requires a constant that
10 characterizes the volumetric change during indentation due to
11 plastic flow of the indented ceramic. A value for the constant
12 is selected that only averages the observed volumetric change
13 of all the different ceramics ever measured. Ideally, the
14 constant should be calibrated through an independent
15 measurement of the toughness of the ceramic.

16
17 Disadvantageously, there is no current known test that can
18 independently measure the fracture toughness of the ceramic
19 balls. The existing fracture toughness test methods are
20 disadvantageously indirect and imprecise because these test
21 methods rely upon a semiquantitative estimate of residual
22 stress. In addition, these have an additional source of
23 imprecision because the residual stress estimate should ideally
24 be calibrated through an independent direct measurement of
25 fracture toughness. Disadvantageously, the existing test
26 methods that directly measure the fracture toughness have only
27 been applied to rectilinear specimens. These and other
28 disadvantages are solved or reduced using the invention.

Summary of the Invention

An object of the invention is to provide fracture toughness measurement method for brittle balls.

Another object of the invention is to provide fracture toughness direct measurement method for brittle balls.

Yet another object of the invention is to provide fracture toughness direct measurement method for brittle balls using applied compressive loads to produce tensile stress.

Still another object of the invention is to provide fracture toughness direct measurement method for brittle balls using applied compressive loads to produce tensile stress while directly observing indentation crack growth.

A further object of the invention is to provide fracture toughness direct measurement method for brittle balls using compressive conforming north-south opposing arc loads while directly observing equatorial indentation crack growth.

The present invention is directed to a mechanical test method for directly measuring the fracture toughness of brittle balls such as ceramic and steel ball bearings. For example, the mechanical test method can be used to directly measure the fracture toughness of the silicon-nitride balls used in hybrid bearings. Using this test method, a starter crack is first

1 placed in the ball at an equatorial position on the surface of
2 the ball. The ball is then placed between opposing platens that
3 have hemispherical sockets with radii equal and conforming to
4 the radius of the spherical ball under test. Importantly, the
5 depth of the hemispherical sockets is less than the radius of
6 the ball, such that the sockets are not a complete hemisphere
7 and such that the angular arc length of the socket from the
8 mating north and south poles of the sockets is less than ninety
9 degrees. Consequently, the middle span of the ball,
10 particularly about the equator of the ball, is not in contact
11 with the hemispherical shaped sockets.

12
13 The starter crack is first positioned at the middle span
14 of the ball along the equator of the ball. Preferably, two
15 opposing platens are pushed towards each other under an applied
16 load along the vertical axis through the respective opposing
17 north and south poles of the two opposing platens. Under the
18 applied load, as the inner socket surfaces apply compression
19 forces upon the ball under test along the conforming angular
20 arc length, the middle span of the ball at the equator slightly
21 bulges outwardly. This equatorial bulging causes a tensile
22 stress in the angular or hoop direction at the middle span
23 along the equator of the brittle ball under test. Under a
24 sufficiently high applied load, a tensile hoop stress develops
25 at the middle span that is intense enough to cause the starter
26 crack to grow in length. The crack growth is preferably
27 directly observed by optical imaging using, for example, an
28 optical microscope. As part of the direct test method of

1 fracture toughness, the fracture toughness is defined by the
2 observed load at which the crack grows and the geometry of the
3 final crack, which naturally provides a stress concentration
4 for the crack. The test method directly provides a measurement
5 of the fracture toughness of the ball under test. The test
6 method is specialized for the spherical brittle balls that may
7 have small spherical volumes. These and other advantages will
8 become more apparent from the following detailed description of
9 the preferred embodiment.

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Bri f Description of the Drawings

Figure 1 is a diagram of a fracture toughness test
fixture.

Figure 2 is a diagram of an indentation crack.

Figure 3 is a flow diagram of a fracture toughness test
method.

Figure 4A is a compressive stress contour plot of a
brittle ball under test.

Figure 4B is a tensile stress contour plot of a brittle
ball under test.

Figure 5 is a crack length to tensile stress graph for
various applied loads.

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Detailed Description of the Preferred Embodiment

An embodiment of the invention is described with reference to the figures using reference designations as shown in the figures. Referring to Figure 1, the mechanical test method can be implemented using a fracture toughness test fixture for directly measuring the fracture toughness of ceramic balls, such as are used in modern hybrid bearings. In practicing the method, a starter crack is first placed in the ball prior to the ball being placed in the test fixture. The ball is placed between opposing platens that have hemispherical sockets with radii equal to the radius of the ball radius. However, the depth of the hemispherical sockets is less than the radius of the ball. That is, the sockets of the platens have a radial arc length that is less than a complete hemisphere such that the conforming arc length is less than ninety degrees from the north pole for the top platen and equally less than ninety degrees for the south pole, so that the midspan or equator of the ball does not contact the incompletely conforming hemispherical sockets because the depth of the sockets is less than the radius of the ball. The depth of the sockets is defined by the conforming angle α . Hence, the incompletely conforming hemisphere sockets are defined by the conforming angle α that is less than ninety degree from the poles, and, in the preferred form, is $75^{\circ} \pm 10$ degree. The nominal 75° off the poles of the platens is an optimum conforming angle α that is also nominally 15° off the equator of the ball.

1 To run the test, the two platens are compressed along the
2 vertical axis extending through the north and south poles of
3 the two platens as well as the ball under test. Using this
4 vertically aligned pole orientation, the ball is compressed by
5 the platens at the north pole and south pole. The middle span
6 at the equator of the ball is not in contact with the
7 incompletely conforming hemispherical sockets. A load cell is
8 used for providing a measurement of the applied load. The load
9 frame uses a push rod to apply the load to the top platen being
10 pushed under the applied load towards the bottom platen
11 supporting the ball under test. The top platen is supported by
12 and moves through a linear bearing. The load frame may be an
13 adapted Instron load frame. The ball rests in the conforming
14 socket of the bottom platen. The linear bearing is disposed
15 between left and right frame brackets coupled and supported by
16 a base in which is disposed the bottom platen. Under a nominal
17 applied load, the push rod pushes the top platen through the
18 linear bearing towards the bottom platen until the conforming
19 socket of the top platen makes contact with the ball under test
20 with the north poles and south poles of the top and bottom
21 sockets aligned with the north and south poles of the ball
22 under test. At the time of contact, the applied load increases
23 so as to apply a compressive force upon the ball across the
24 conforming sockets. The middle equator of the ball begins to
25 bulge outwardly as the applied load is increased, causing a
26 tensile stress in a hoop direction at the equator. The starter
27 precrack begins to grow under the tensile stress. The starter
28 precrack can be as great as 1.33 mm. An imaging device, such as an

1 optical motion microscope, can be used to image the crack
2 growth while the ball is under the applied load, such that the
3 test fixture can provide measurements of crack growth under the
4 applied load, from which the fracture toughness can be
5 automatically computed by a computer that receives the crack
6 growth data from the microscope and applied load data from the
7 load cell. The microscope can be adapted to include or couple
8 to a computer processor receiving applied load data from the
9 load cell while further receiving crack growth data from the
10 microscope.

11
12 Referring to Figures 1 and 2, and more particularly to
13 Figure 2, an indentation is placed in the ball. Conventional
14 indentations methods can be used that employ a hard diamond
15 tool having a pyramidal point that is struck into the surface
16 of the ball. When struck, a starter surface latitudinal crack
17 is disposed in a half penny latitudinal crack and a starter
18 surface longitudinal crack is disposed in a half penny
19 longitudinal crack. Under the applied stress, the starter
20 surface longitudinal crack grows to a final surface
21 longitudinal crack. Longitudinal crack growth is imaged and
22 measured by the crack motion microscope as a function of the
23 applied load measured by the load cell. The microscope can
24 image the radial distance from the center of the pyramidal
25 indent to the further extent of the surface crack so as to
26 measure the time rate of change of crack growth relative to an
27 applied load.

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1 Referring to Figures 1, 2, and 3, and more particularly
2 Figure 3, the test method is preferably implemented using a
3 manufactured test fixture, such as the preferred fracture
4 toughness test fixture shown in Figure 1. A brittle ball is
5 manufactured. The brittle ball can be made of various
6 materials, such as from ceramics and steel. Destructive starter
7 precracks are struck into the ball. The precracks are
8 preferably created on the surface of the ball when struck by a
9 conventional Vickers diamond tool having a pyramidal point for
10 creating the indentation in the ball under test. When striking
11 the ball, the longitudinal and latitudinal surface starter
12 cracks are formed. Hence, the placement of the indentation on
13 the surface of the ball defines the north and south poles
14 aligned to two opposing vertical corners of the indentation
15 that point longitudinally toward the north and south poles, and
16 defines the horizontal equator of the ball aligned with two
17 opposing horizontal corners of the indentation, such that, the
18 two longitudinal starter precracks are aligned towards the
19 poles and the two latitudinal starter precracks are aligned
20 with the equator. As such, the indentation defines the desired
21 placement of the ball in the bottom platen of the test fixture.
22 Imaging the indentation as well as the longitudinal starter
23 precracks with respect to alignment in the bottom platen can
24 then optically image the ball to determine that the ball has
25 been accurately disposed in the bottom platen. That is, the
26 ball is positioned in the bottom platen with the starter
27 precrack placed at the equator with the axis of the
28 longitudinal precracks perpendicular to the equator. The

1 longitudinal pr crack points toward the north and south poles
2 while centered on the equator of th ball, which r sts in the
3 conforming socket of the bottom plat n. The load frame applies
4 an initial low push load to the push rod to push the top platen
5 towards the ball until the conforming socket of the top platen
6 makes conforming mating contact with the north hemispherical
7 surface of the ball under test. The load frame then applies an
8 increasing amount of load upon the top platen to apply an
9 increasing amount of load upon the ball. Under a sufficiently
10 high applied load, a tensile hoop stress develops at the
11 equator that is intense enough to cause the precracks to grow.
12 The crack growth is observed directly by the optical
13 microscope. In situ images of the ball under test are captured
14 while the ball is under load. Using conventional computational
15 practices, the fracture toughness is defined by the observed
16 load at which the crack grows and the geometry of the
17 precracks, which defines the stress concentration. The fracture
18 toughness is directly computed from the crack growth, the
19 geometry of the precracks, and the applied load. The test
20 method is specialized for the spherical balls that may have
21 small spherical volumes.

22
23 Referring to Figures 1, 2, 3, 4A and 4B, and particularly
24 Figures 4A and 4B, compressive stresses and tensile stresses
25 are created in the ball under test, as well the top platen. Of
26 particular interest is the hoop tensile stress that develops at
27 the equator when th ball is compressed at the two poles. The
28 tensile stress can be calculated using finite element analysis.

1 An axisymmetric calculation can be performed to show the
2 compressive and tensile stresses in a slice through the ball
3 under test. The gradation from high, medium, low, and very low
4 compressive stress and tensile stress extends through the ball
5 and platen. The tensile stresses are highest at the equator.
6 The compressive applied load is effectively translated into
7 hoop tensile stress at the equator of the ball under test.

8
9 Referring to all of the Figures, and particularly to
10 Figure 5, isocontours are shown for maximum principal stresses
11 in MPa as a function of the radial position at the equator for
12 different applied loads in Newtons N. As shown, the isocontours
13 are relatively flat across radial position. The longitudinal
14 precrack grows in the north and south directions from the top
15 and bottom edges of the longitudinal precracks. The north and
16 south directions are orthogonal to the applied tensile hoop
17 stresses at the equator. Therefore, the north to south
18 direction is the preferred direction for crack growth. The
19 starter precrack is modeled as a half penny crack. The half
20 penny cracks are characterized by two dimensions including the
21 length $2C$ of the crack at the surface and the depth A of the
22 crack. The stress intensity factor K for the half penny crack is
23 a function of the ratio A/C and the square root of depth A and
24 is given by the K fracture toughness equation, $K=[1.13-$
25 $0.09(A/C)]\sqrt{[\pi/Q\sigma\sqrt{A}]}$. In the fracture toughness equation,
26 $Q=1+1.464(A/C)^{1.65}$, the term σ is the applied tensile stress
27 field, K is the fracture toughness, Q is a geometric factor, C
28 is the half penny crack radius on the surface, and A is th

1 half penny crack radius into the depth of the material. The
2 ratio A/C is one when the half penny crack is a perfect half
3 circle. Mathematically, K has two terms that are proportional
4 to the depth A and one term that is inversely proportional to
5 A . For this reason, K is not a strong function of the depth A
6 because the proportional and inversely proportional terms
7 counterbalance. Hence, the starting half penny precrack can
8 tolerate errors in characterizing depth A for a given value of
9 the length C . Therefore, the fracture toughness K depends more
10 strongly on σ than on the depth A , for a given value of length
11 C . Hence, the computation accurately provides the fracture
12 toughness K when the length C can be measured accurately, even
13 when the depth A can not be accurately measured.

14
15 For example, the applied stress field can be calculated by
16 finite element analysis. The stress field at the equator for
17 different loads applied of the fixture can be determined for
18 balls of differing materials. Along the x-axis of the
19 isocontours, a radial distance of 0.0 mm corresponds to the
20 outer diameter of the ball. An increasing radial distance
21 represents an increasing depth into the ball from the surface.
22 Hence, a half penny crack that is 0.5 mm deep, where $A=0.5$ mm,
23 is at a radial distance of 0.5 mm. The y-axis of the
24 isocontours provides the maximum principal stress as a function
25 of load applied into the test fixture. The maximum principal
26 stress is tensile and is the stress component responsible for
27 fracture during the test. To calculate the fracture toughness K

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1 from the fracture toughness equation, the maximum principal
2 stress is used as the applied tensile stress field σ .

3
4 Images of a ball are obtained for crack growth at an
5 applied load, for example, of 6003 N, with the starter precrack
6 positioned at the equator of the ball between the platens and
7 under a load of 5000 N before crack growth occurred. Successful
8 formation of crack growth from the starter precrack may occur
9 at an exemplar applied load of 6003 N. Imaging magnifications
10 may be at 100x for crack growth recognition. Florescent
11 backlighting may be used for highlighting the precrack and
12 crack growth. An image of the surface of the precrack can
13 provide a value for length C, but depth A is not directly
14 known. However, it is commonly known that a Vickers indentation
15 provides a circular precrack for which $A/C=1$. For example, with
16 a crack length of $2C=1.56$ mm, $A=0.778$ mm by direct inference.
17 For such an exemplar precrack, the crack is imaged to grow at
18 an applied load of 6003 N. From the isocontours, an applied
19 load of 6003 N provides a maximum principal stress of $\sigma=16.0$
20 MPa at $A=0.778$ mm by interpolating between applied load
21 isocontours. From the fracture toughness equation, the fracture
22 toughness is computed to be $K=0.52 \text{ MPa}\sqrt{\text{m}}$ which compares to the
23 handbook values for glass, for example.

24
25 To test the sensitivity of the calculation to errors in
26 the value of A/C , with $A/C=0.5$, and $A=0.39$ mm, using a Vickers
27 indentation. The applied load isocontours are very flat over
28 the typical range of A for the experimentally measured applied

1 loads. Hence, the value of σ is unchanged at a value of 16
2 MPa. From fracture toughness equation, $K=0.50 \text{ MPa}\sqrt{\text{m}}$. Remarkably,
3 the calculated fracture toughness is relatively immune to
4 errors in characterizing the ratio A/C. In addition, because
5 the applied load isocontours are very flat, the value of σ used
6 in fracture toughness equation is also relatively immune to
7 errors in characterizing both the depth A and the ratio A/C.
8 Hence, the proposed mechanical test method is immune to errors
9 in measuring A and A/C because the maximum principal stress is
10 uniform over the relevant size scale of the typical precrack
11 because of the uniform isostress contours. Hence, the test is
12 also equally immune to errors in positioning the precrack at
13 the equator even when the errors in positioning the ball in the
14 bottom platen are of the order of the length scale of the
15 precrack. The uniformity of the applied tensile stress field
16 makes the test robust and offers repeatable manufacturing
17 precision.

18
19 The invention is directed to a test method that directly
20 images crack growth at an applied load for directly computing
21 the fracture toughness of brittle balls. The method is precise,
22 rigorous, immune to errors, and is fully quantitative. The ball
23 under test is compressed along the north and south poles of the
24 ball, which causes the equatorial bulging under high tensile
25 stresses where crack growth occurs at a sufficiently high
26 applied load. Ball is precracked preferably by a diamond
27 indenter. The longitudinal precracks created by the indentation
28 are placed at equator and point vertically towards the north

1 and south poles of the ball. Th ball is compressed by
2 conforming north and south opposing hemispherical platen
3 sockets generating hoop tensile stress s at equator wh re the
4 longitudinal crack growth occurs at the sufficiently high
5 applied load. The fracture toughness is directly computed from
6 imaging of the crack length and known values of the applied
7 stress for the critical load at which the crack grows unstably.
8 The conforming mating hemispherical platens are incompletely
9 conforming, that is less than 90° in arc length angle from the
10 poles. Too low an angle and the ball is crushed at the poles.
11 At too high an angle, the equator does not bulge to give
12 required tensile hoop stress. Finite element analysis shows
13 that an arc length angle α of $75^\circ \pm 10^\circ$ is preferred. The test
14 method measures the fracture toughness of a wide variety of
15 brittle material balls including ceramics and steel ball
16 bearings, such as 52100 steel bearing class balls with fracture
17 toughnesses K up to $15.0 \text{ MPa}\sqrt{\text{m}}$ with precracks preferably having
18 a length $2C$ of greater than 1.3 mm . The test method enables
19 direct measurement of the fracture toughness of ball bearings,
20 such as silicon-nitride balls used in hybrid bearings. The
21 method can be used by ball bearing manufacturers for screening
22 lots of balls for fracture toughness requirements. The test can
23 be applied using variously sized indenters and balls of
24 differing materials and sizes. Those skilled in the art can
25 make enhancements, improvements, and modifications to the
26 invention, and these enhancements, improvements, and
27 modifications may nonetheless fall within the spirit and scope
28 of the following claims.